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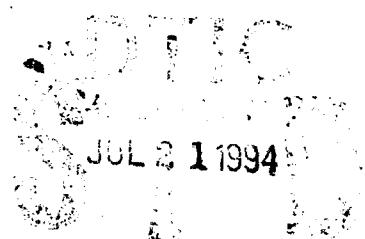
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# High Current Density Sheet-Like Electron Beam Generator

Cora Chow-Miller  
Eric Korevaar  
John Schuster

AstroTerra Corporation

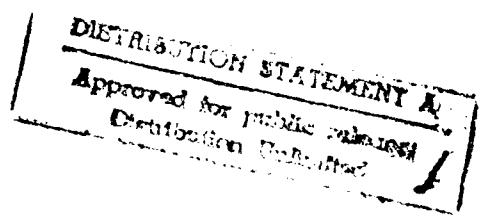
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# **High Current Density Sheet-Like Electron Beam Generator**

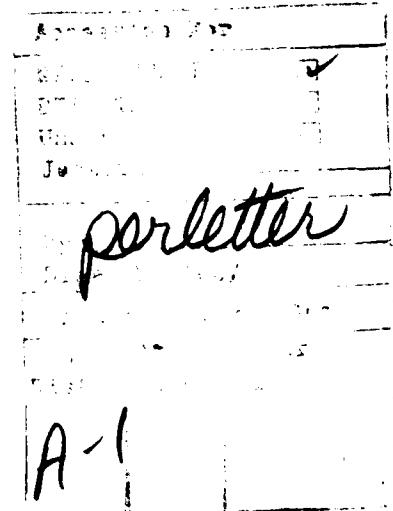
Prepared by  
**Eric Korevaar**  
**Cora Chow-Miller**  
**John Schuster**

**AstroTerra Corporation**  
11689 Sorrento Valley Rd. Suite A  
San Diego, CA 92121

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## **Abstract**

Sheet electron beams are very desirable for coupling to the evanescent waves in small millimeter wave slow-wave circuits to achieve higher powers. In particular, they are critical for operation of the free-electron-laser-like Orotron. This program was a systematic effort to establish a solid technology base for such a sheet-like electron emitter system that will facilitate the detailed studies of beam propagation stability. Specifically, the effort involved the design and test of a novel electron gun using Lanthanum hexaboride ( $\text{LaB}_6$ ) as the thermionic cathode material. Three sets of experiments were performed to measure beam propagation as a function of collector current, beam voltage, and heating power. The design demonstrated its reliability by delivering 386.5 hours of operation throughout the weeks of experimentation. In addition, the cathode survived two venting and pump down cycles without being poisoned or losing its emission characteristics. A current density of  $10.7 \text{ A/cm}^2$  was measured while operating at 50 watts of ohmic heating power. Preliminary results indicate that the nearby presence of a metal plate can stabilize the beam.

## **TABLE OF CONTENTS**

<b>ABSTRACT</b>	<b>iii</b>
<b>SUMMARY</b>	<b>1</b>
<b>INTRODUCTION</b>	<b>3</b>
<b>METHODS, ASSUMPTIONS, AND PROCEDURES</b>	<b>5</b>
<b>RESULTS AND DISCUSSION</b>	<b>17</b>
<b>CONCLUSIONS</b>	<b>30</b>
<b>RECOMMENDATIONS</b>	<b>31</b>
<b>REFERENCES</b>	<b>32</b>

## List of Figures and Tables:

Figure 1.	High current density sheet-like electron emitter design.	6
Figure 2.	Novel vacuum fixture with permanent magnets.	7
Figure 3.	Magnetic field strength along the axis of the sheet beam.	8
Figure 4.	Novel test fixture with diagnostic instrumentation.	10
Figure 5.	Photograph of the test apparatus.	11
Figure 6.	Sheet electron beam current probe assembly.	11
Figure 7.	Schematic of sheet beam electrical test system.	13
Figure 8.	Schematic of beam stability measurement diagnostic.	15
Figure 9.	Schematic of beam stability measurement diagnostic with metal plate.	16
Figure 10.	Sheet beam current distribution diagnostic.	16
Figure 11.	Beam current as a function of beam voltage for different ohmic power levels.	17
Figure 12.	Sheet beam current distribution along the axis of propagation.	19
Figure 13.	Collector current measured from the phosphor screen.	20
Figure 14.	Sheet-like electron beam profile.	22
Figure 15.	Test data: typical current waveform.	23
Figure 16.	Coordinate geometry for measurements.	25
Figure 17.	Positions where beam current was measured.	25
Figure 18.	Measured current vs. Z position for probe #3 at 140 degrees angle.	26
Figure 19.	Electron beam current profile across the width of the beam at $y = -10\text{mm}$ .	27
Table 1.	Measured thickness and intercepted beam current as a function of x and y.	28
Figure 20.	Electron beam current and thickness as a function of position.	29

## **Summary**

Microwave power tubes using sheet-like electron beams can potentially deliver greater output power than those with conventional solid cylindrical beams. Furthermore, sheet beams can be thin enough to permit good coupling to the evanescent waves in small millimeter wave slow-wave circuits. In particular, they are critical for operation of the free-electron-laser-like Otron. These advantages justify additional theoretical and experimental studies on the generation and stable propagation of sheet beams. Unfortunately, nearly all microwave power tubes currently on the market use electron sources that cannot be subjected to frequent venting and pump down cycles without being poisoned or losing their emission characteristics. This poses a serious obstacle to the research and development of stable sheet beams. Therefore, rugged cathodes which can deliver large electron emission over a long life are needed. This program was a systematic effort to establish a solid technology base for such a sheet-like electron emitter system. Specifically, the goal was to design and build a reliable high current density sheet-like electron generator to facilitate detailed studies of the stable propagation of sheet-like electron beams.

This contract involved the design and test of a novel sheet-like electron gun using Lanthanum hexaboride ( $\text{LaB}_6$ ) as the cathode material.  $\text{LaB}_6$  was selected as the thermionic cathode because of its resistance to poisoning in modest vacuum and its ability to produce high current density and high brightness electron beams. Most of the previous work with  $\text{LaB}_6$  has been limited to cathodes with small circular cross sections, whereas our filament is a 10mm x 0.3mm slab. Two pyrolytic graphite bars sandwiched on either side of the filament were ohmically heated to provide the heat source. Heat was generated by passing a current along the short direction, taking advantage of the high electrical resistivity and low thermal conductivity along the c-direction of the pyrolytic graphite. Our design was based on the following key insights, which may have been lacking in previous investigations: (1) Additional pyrolytic graphite bars were employed as thermal insulators, which increased heater efficiency. (2) Permanent magnets were arranged to provide a converging magnetic field to increase current density in the interaction region. (In the Otron, close interaction between the beam and the surface of a grooved metal grating can increase power output.) The magnetic field can be adjusted to optimize the convergence of the electron beam in the interaction region. The design

demonstrated its reliability by delivering 386.5 hours of operation for the duration of the experiment. In addition, the cathode survived two venting and pump down cycles without being poisoned or losing its emission characteristics. A current density of  $10.7 \text{ A/cm}^2$  was measured while operating on 50 W of ohmic heating power. This novel design led to a rugged high current density electron emitter that will facilitate detailed studies of the stable propagation of sheet-like electron beams.

A thin sheet electron beam confined by a magnetic field does not maintain its initial shape, but eventually breaks up into a series of curved fragments. This occurs because any initial local disturbances in the beam, such as a deflection or density variation, give rise to an imbalance in the space charge field in such a direction as to further increase the disturbance. This indicates a beam instability. Research and experimentation on the techniques to suppress these instabilities are necessary for application of these beams in microwave power tubes.

Three sets of experiments were performed. They were devised to measure beam profile as a function of total current, beam voltage, and heating power. First, the shape of the beam during propagation was observed on a phosphor screen, which was attached to a linear actuator. The screen provided a detailed view of the beam profile along the length of the propagation path. Second, a short metal plate was placed parallel to the electron beam in front of the phosphor screen. This enabled us to visually verify the stabilizing effect of the beam's interaction with the plate surface, which simulates the grating configuration in a mm wave source device such as the Otron. Finally, a full length (5 cm) metal plate was installed and a special current probe was used to map out the beam current distribution.

Preliminary results indicate that the nearby presence of a metal plate stabilizes the beam. The rugged high current density sheet-like electron emitter system enables the systematic study of beam propagation under various electron device configurations.

## **Introduction**

The purpose of this contract effort was to demonstrate the feasibility of a high current sheet-like electron beam source using a rugged cathode. There are several important advantages to be gained from the availability of a reliable sheet-like electron beam generator. Microwave power tubes employing sheet-like electron beams can potentially deliver greater output power than those with conventional solid cylindrical beams. Furthermore, sheet beams can be thin enough to permit good coupling to the evanescent waves in small millimeter wave slow-wave circuits<sup>(1)</sup>. In particular, they are critical for operation of the free-electron-laser-like Otron. This is very important for scaling the novel microwave tube concepts to higher frequencies since the allowed interaction volume is decreased<sup>(2)</sup>. These advantages justify additional theoretical and experimental studies on the generation and stable propagation of sheet beams. Unfortunately, nearly all microwave power tubes currently on the market use electron sources that cannot be subjected to frequent venting and pump down cycles without being poisoned or losing their emission characteristics. This poses a serious obstacle to the research and development of stable sheet beams. As a result, rugged cathodes that can deliver large electron emission over a long life are needed.

This program was a systematic effort to establish a solid technology base for such an electron emitter system. Later, this system can be used to facilitate detailed studies of the propagation of these beams under various electron device configurations. Specifically, the goal was to build a reliable high current density ( $>20\text{A}/\text{cm}^2$ ) sheet-like electron source that optimizes current density to heating power ratio. This contract effort involved the design, test and demonstration of a novel sheet-like electron gun using Lanthanum hexaboride ( $\text{LaB}_6$ ) cathode material.

Our design was based on the following key insights, which may have been lacking in previous investigations of high current density cathodes: (1) To increase heater efficiency, pyrolytic graphite bars were employed as thermal insulators. (2) Permanent magnets were arranged to provide a converging magnetic field, to increase current density in the desired interaction region, which is at the surface of a metal plate. (In the Otron, the interaction region is the surface of a grooved metal grating.)

A thin sheet electron beam confined by a magnetic field does not maintain its initial shape, but eventually breaks up into a series of curved fragments<sup>(3)</sup>. This occurs because any initial local disturbances in the beam, such as a deflection or density variation, give rise to an imbalance in the space charge field in such a direction as to further increase the disturbance. This indicates a beam instability<sup>(4,5)</sup>. Research and experimentation on the techniques to suppress these instabilities are necessary for application of these beams in microwave power tubes.

Our novel design has led to a rugged high current density electron gun that will facilitate detailed studies of the stable propagation of sheet-like electron beams. Three sets of experiments were devised to measure beam profile as a function of collector current, beam voltage, and heating power. These experiments enabled us to verify the reliable operation of the sheet-like electron emitter system. The preliminary results suggest techniques for the optimization of the novel electron gun in the Orottron.

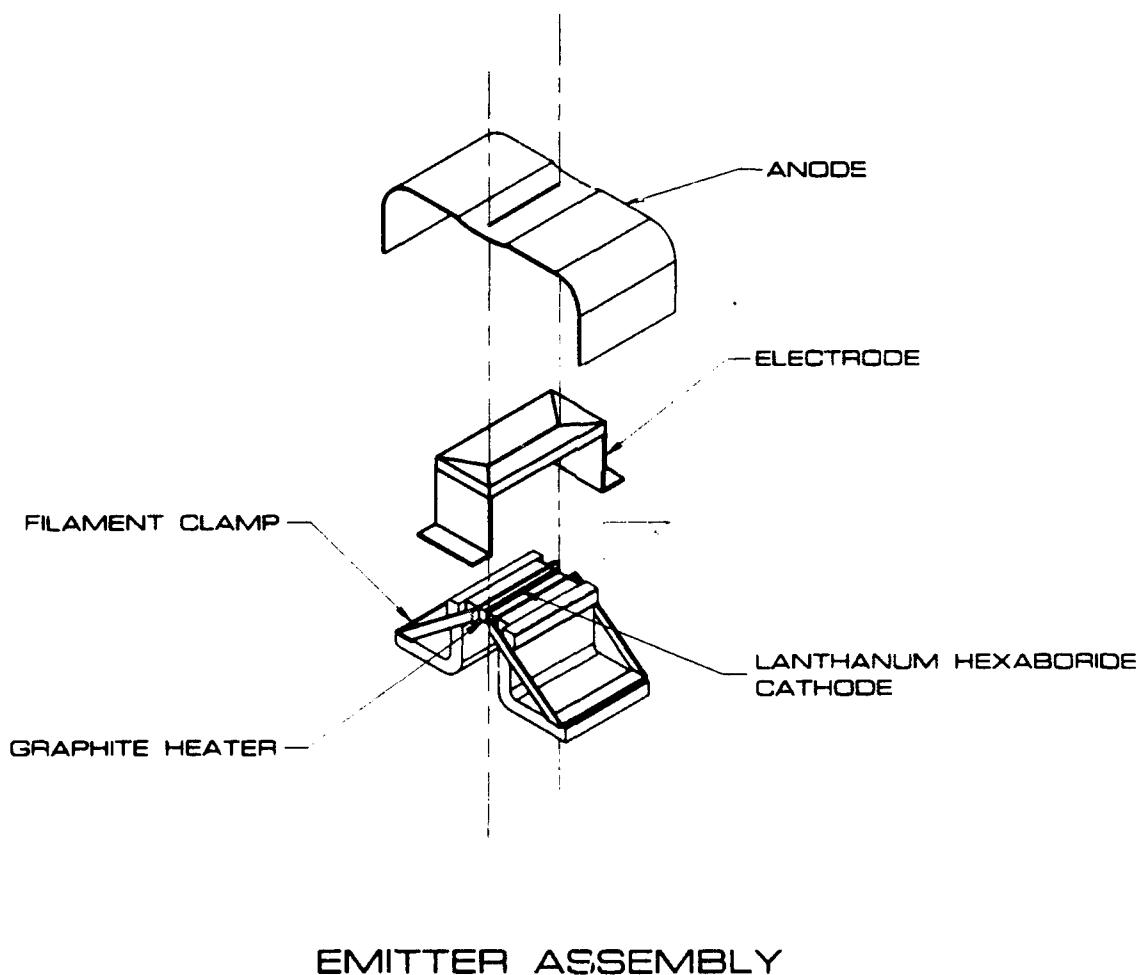
## Methods, Assumptions, and Procedures

This program was a systematic effort to establish a solid technology base for a sheet-like electron emitter system which can be used to facilitate detailed studies of the propagation of these beams under various electron device configurations. Specifically, the goal was to build a reliable high current density ( $>20\text{A/cm}^2$ ) sheet-like electron source that optimizes current density to heating power ratio. This contract effort involved the design, test, and optimization of a novel sheet-like electron gun using Lanthanum hexaboride ( $\text{LaB}_6$ ) cathode material.

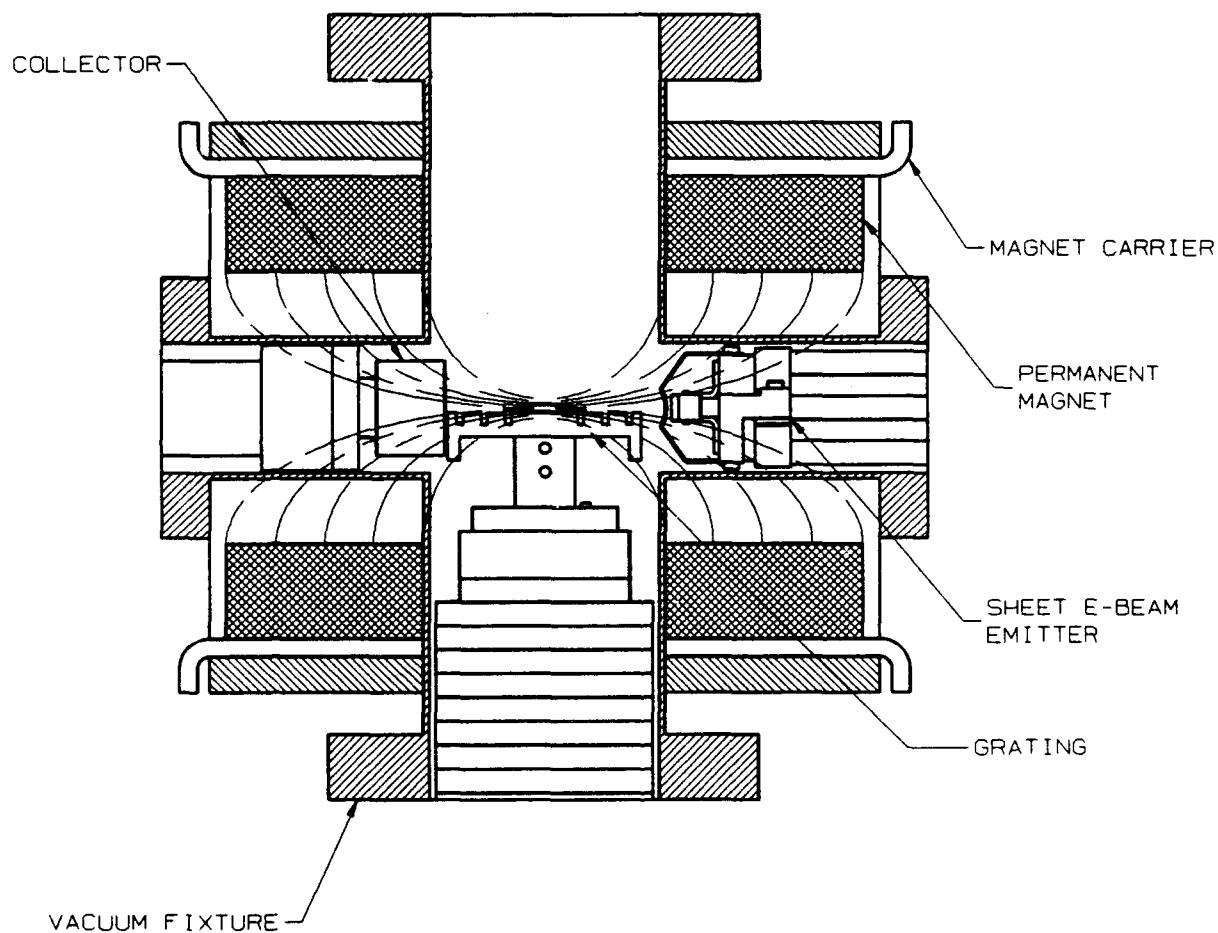
$\text{LaB}_6$  was selected as the thermionic cathode material because it delivers high current density and high brightness electron beams at substantially lower temperatures than other rugged emitters. It is also better suited to applications requiring electron beams that are pulsed at a high repetition rate or are continuous wave. Furthermore, other researchers have reported that  $\text{LaB}_6$  cathodes at a temperature of  $1400\text{ }^\circ\text{C}$  are resistant to poisoning in modest vacuum (on the order of  $10^{-5}\text{ Torr}$ ). This resistance to poisoning also increases with increasing temperature. Related experimental developments have shown that a novel  $\text{LaB}_6$  cathode design can lead to a rugged and reliable emitter.

The primary goal was to operate with the lowest ohmic heating power necessary for a given output current and beam geometry. Since the electrical resistivity of  $\text{LaB}_6$  is very low, heating it directly would be very inefficient. Instead, the filament was sandwiched between two pyrolytic graphite bars and heat was generated by passing a current along the short direction. This took advantage of the high electrical resistivity and low thermal conductivity along the c-direction of the pyrolytic graphite. In addition, two pyrolytic graphite bars were positioned to insulate the heater from the clamps. This design led to an increase in the filament temperature and reduced the heating current. Figure 1 shows the  $\text{LaB}_6$  emitter assembly.

It is important that both the electron gun and the metal plate are immersed in a uniform magnetic field with magnetic flux in the same direction as the electron flow. The electron beam was steered and compressed by the field, increasing current density in the desired interaction region, as shown in figure 2. For this experiment, a copper plate was used instead of the grating in an orotron. The electron beam passed just above the plate surface so that close interaction



**Figure 1.** High current density sheet-like electron emitter design. Arrow indicates the direction of current flow.



**Figure 2.** Novel vacuum fixture with permanent magnets to provide a converging magnetic field.

could be achieved. The fixture supporting eight permanent magnets was designed to cradle the vacuum chamber such that the magnetic field would surround the electron gun. Measurements were taken to map the magnetic field inside the vacuum chamber with respect to the test fixture. The magnetic field inside the chamber can be varied by moving the magnets. At the closest spacing allowed by the vacuum fixture, the measured magnetic field has a field strength of 2.36 kGauss and is extremely uniform over the interaction volume. A graph of the measured axial field as a function of position is shown in figure 3. Moving the magnets farther apart reduces the peak strength of the center field. Moving them closer together increases the center field strength, leading to greater convergence of field lines in the center, but reduces uniformity. For the uniform field case, the cathode can either be placed in the high field or further back where the field lines are converging. The beam propagation stability and current distribution were studied for the uniform field case.

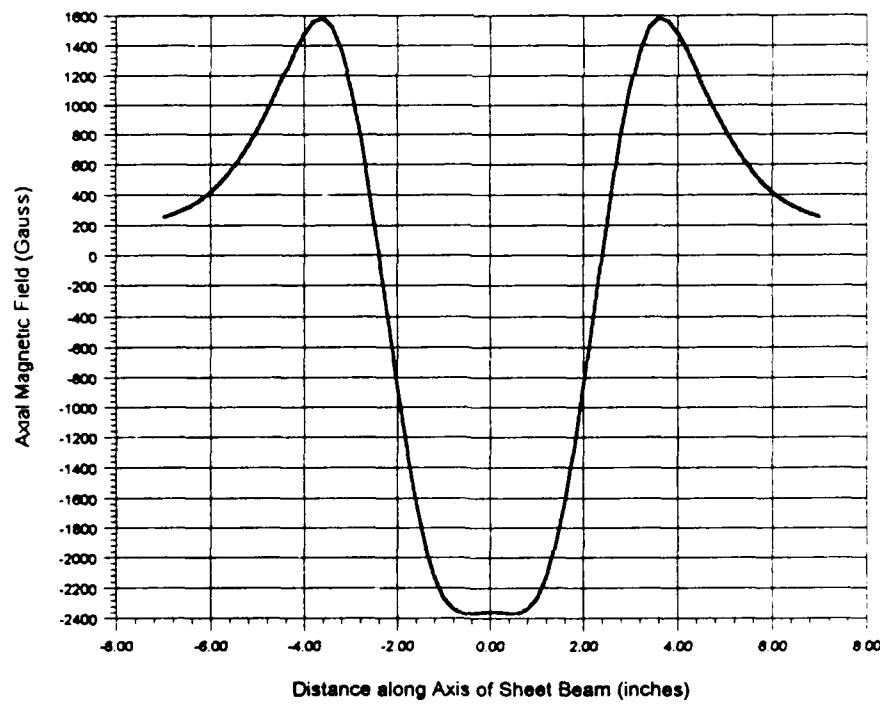


Figure 3. Magnetic field strength along the axis of the sheet beam. The designed interaction length in a uniform field is 2 inches (5 cm).

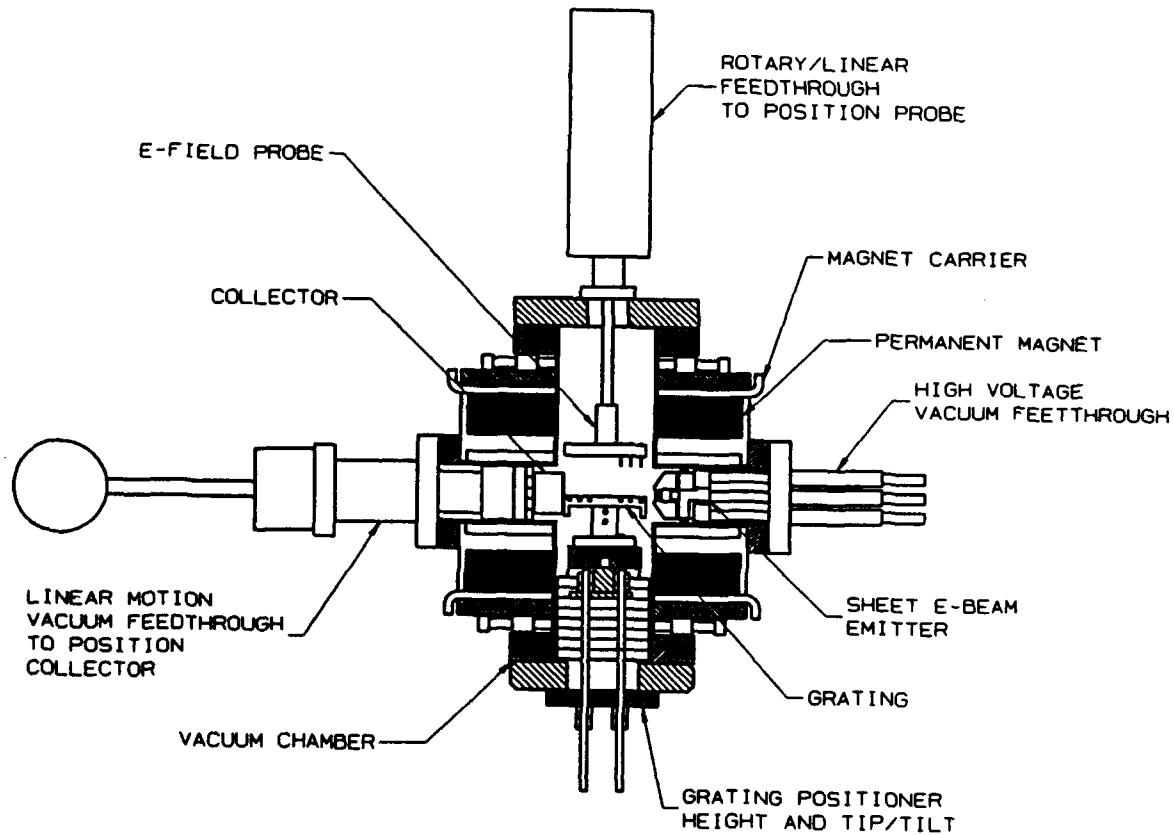
The vacuum chamber was a reducing 6-way cross consisting of three cylinders intersecting at their mid points at right angles to each other. The two smaller cylinders had a 1.5 inch (3.8 cm) outer diameter and standard 2.75 inch (7 cm) diameter flanges. The larger cylinder had 3 inch (7.6 cm) outer diameter and 4.50 inch (11.4 cm) diameter flanges. The test fixture is depicted in figure 4. A photograph of the test apparatus, including the vacuum chamber, electron gun, and diagnostics, is provided in figure 5.

The emitter assembly screwed directly onto the ends of four high voltage vacuum feedthroughs on a standard bulkhead. This enabled the entire gun assembly to be bolted into one end of a smaller cylinder. The collector was attached to a linear motion vacuum feedthrough and was installed inside the opposite end of the same cylinder. A viewing port and the pump connection were located on the opposite ends of the second small cylinder.

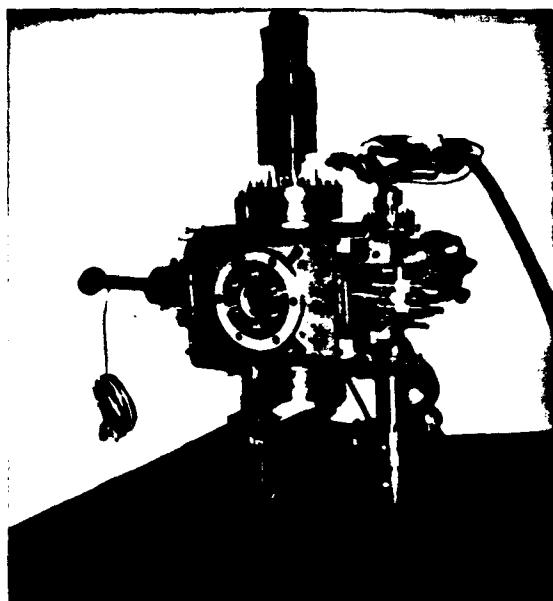
It was very important for the electron beam to propagate very close to the surface of the metal plate for efficient operation. (In the Orotron, the interaction thickness above the grating is comparable to the grating pitch on the order of 0.5mm.) The metal plate's linear translation system included a tip/tilt piston stage. This provided full adjustment capability to ensure proper interaction between the electron beam and the plate surface.

A special current diagnostic, shown in figure 6, was designed to measure the electron beam current density at various locations above the metal plate. Using a combination of rotary and linear motion, the probe can be positioned at various locations to measure current density and beam thickness. The location of the electron beam determined the best place for the metal plate.

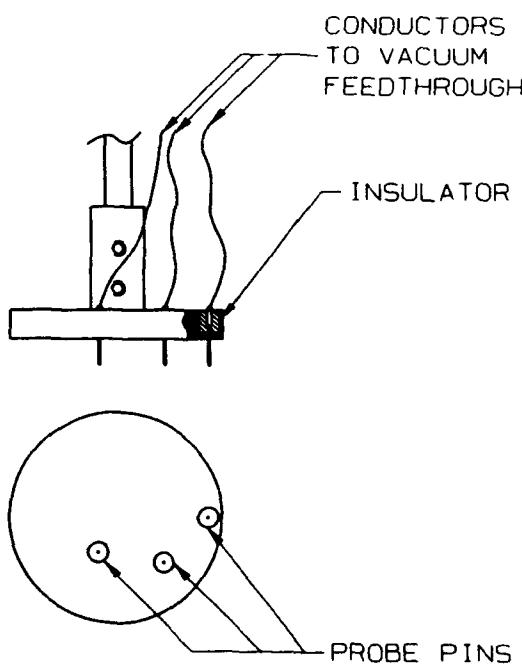
The vacuum system was constructed in anticipation of frequent ventilation and pump-down cycles during this experimental program. It consisted of an oil-less membrane pump followed by a large ion pump. An ion gauge was used so that the vacuum condition could be monitored continuously. The oil-less pump took the system down to the middle of the  $10^{-6}$  torr range, then the ion pump was used to take the system down to  $10^{-7}$  torr range. Initially, the system was baked overnight at approximately 100 °C, which is the temperature limit of the rotary-linear actuator. After all the moisture was removed, the electron gun system was generally operated with chamber pressure in the  $10^{-7}$  torr range during the experiments.



**Figure 4. Novel test fixture with diagnostic instrumentation to measure current density.**



**Figure 5. Photograph of the complete test apparatus.**



**Figure 6. Sheet electron beam current probe assembly.**

A schematic of the electrical system is shown in figure 7. Existing test equipment at ThermoTrex Corporation(TTC) was made available to us under subcontract. This consisted of a high voltage power supply, a floating power deck, and a pulse generator circuit. The high voltage power supply is capable of delivering up to 20kV at 200mA continuously. For this project, the high voltage was limited to 5kV or less. The power deck consists of a high current AC power supply for the emitter assembly and a power supply for the focus electrode. The power deck was isolated from ground through a one to one isolation transformer. The transformer secondary winding was connected to the high voltage power supply. This determined the cathode potential, which was negative.

The electron beam was pulsed to deliver higher current. The anode was pulsed from the cathode's negative potential to ground for approximately  $2\mu s$  at 100 Hz. The anode was pulsed high instead of pulsing the cathode low, because the anode drew only a few milliamp of current. The anode was connected to the cathode through a charging resistor and then connected to ground via a current limiting resistor in series with a FET switch. This FET was essentially a variable resistor, switching between  $100M\Omega$  and a few hundred ohms. The switch pulled the anode potential up to ground from the cathode potential (-3kV) during the pulse on cycle. The pulse rise time was determined by the anode electrode capacitance and the series  $5k\Omega$  resistor. The anode returned to the cathode potential during the off cycle. The pulse fall time for the anode was determined by the anode charging resistor ( $10k\Omega$ ) and the series  $5k\Omega$  resistor and was therefore three times that of the rise time.

The LaB<sub>6</sub> emitter assembly was heated by the AC voltage from a variac combined with a step down transformer. The heater voltage was filtered by a low inductance energy storage capacitor ( $0.1\mu F$ ) in paralleled with a  $50M\Omega$  bleeder resistor. Heater current up to 15A was applied. The electron beam pulse voltage could vary depending on its relative phase with respect to the line voltage. The solid state switch had to be pulsed synchronously with the line voltage, so a special circuit was used to detect every line voltage zero crossing and to generate a trigger signal for the solid state switch. This circuit also included pulse width, duty cycle, and delay control. The pulse width was variable from  $0.5\mu s$  to  $2.5\mu s$ . Maximum pulse rate was 120 Hz, the line voltage zero crossing frequency.

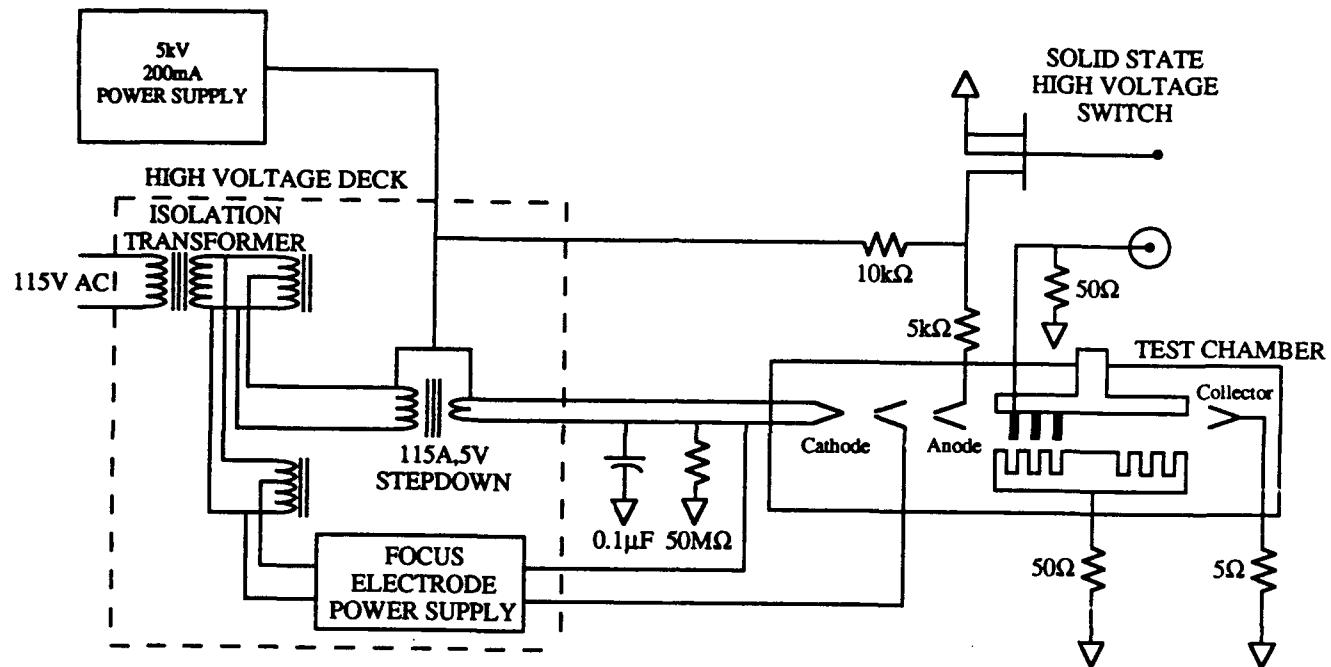


Figure 7. Schematic of sheet beam electrical test system.

Electrical performance of the device was monitored by a set of voltage and current diagnostics. The cathode heating power was calculated from the current and voltage measured at the power supply. The cathode potential was controlled from the front panel of the regulated high voltage power supply. The anode pulse voltage was measured by a 1000:1 Tektronix high voltage probe. The collector was terminated to ground through a  $5\Omega$  resistor and the metal plate was terminated to ground through a  $50\Omega$  resistor. The voltage on the plate and collector outputs represented the beam currents that each apparatus received. In addition, the beam current was sampled with the current probe to determine the beam width, beam thickness, and current density distribution. The probe was designed to intercept a small fraction of the beam current without

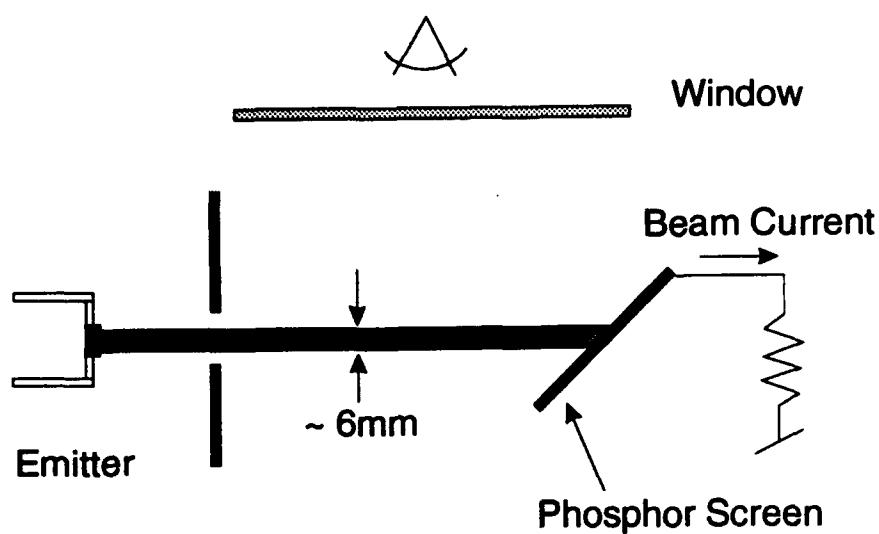
disturbing beam stability. Each pin on the probe picked up an amount of current which was proportional to the beam area it intersects, thus providing good resolution but not interfering with beam propagation. The probe was attached to a micrometer and was incrementally lowered into the beam. Each increase in pin current gave the current density for that position. Six cross sections of the beam were measured along the length of the beam. On the average, current at five points was measured across the width of each section.

The objective of this effort was to demonstrate the feasibility of a reliable, high current capable sheet electron gun using LaB<sub>6</sub> as the cathode material. Toward this goal, we designed and conducted experiments to document performance of the sheet electron gun shown previously in figure 1.

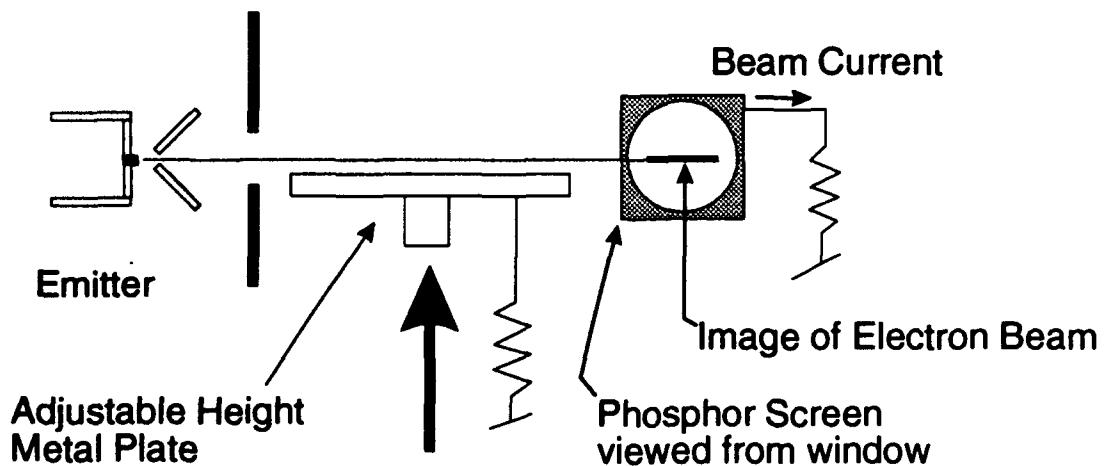
The design characteristics of the sheet electron emitter assembly are as follows:

LaB <sub>6</sub> filament	0.3 mm x 10 mm x 1.5 mm
Pyrolytic graphite	1 mm x 11 mm x 1 mm (heater bar) 1.5 mm x 11 mm x 1 mm (thermal insulator)
Heater leads	5 mils thick x 2 mm x 4 cm
Cathode clamp	TZM, a molybdenum alloy
Focus electrode	tantalum
Anode	tantalum
Base plate	1.375 inch diameter x 0.375 inch thick ceramic

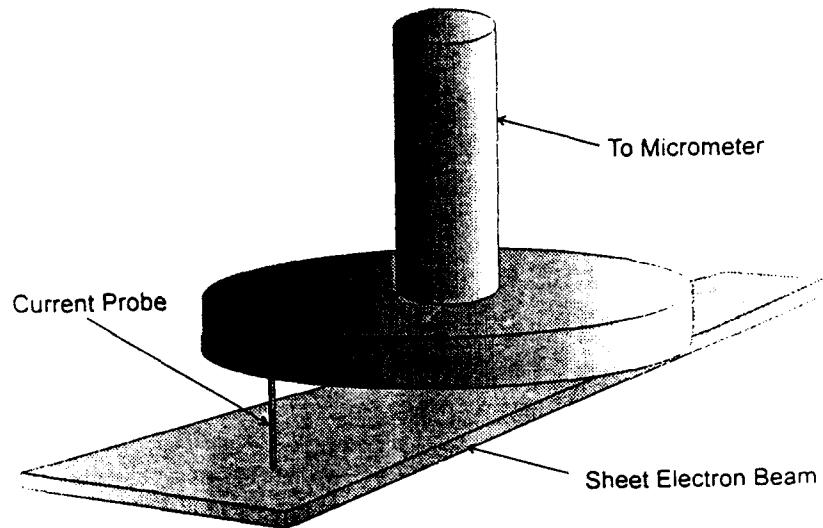
Three sets of experiments were performed. They were devised to measure beam profile as a function of total current, beam voltage and heating power. First, the shape of the beam during propagation was observed on a phosphor screen as illustrated in figure 8. The phosphor screen (collector) was attached to a linear actuator which allowed it to move in order to intersect the sheet beam at various locations. This provided a detailed view of the beam along a large section of the propagation path. Second, a short metal plate was placed in front of the collector below and parallel to the electron beam, and as close as possible to it. The phosphor screen remained visible from the window. This set up is shown in figure 9. This enabled us to evaluate the stabilizing effect of the beam's interaction with a metal plate, simulating the grating configuration in a mm wave source device such as the Otron. Finally, a full length metal plate was installed and the current probe was used to map out the beam current distribution as illustrated in figure 10.



**Figure 8.** Schematic of beam stability measurement diagnostic.



**Figure 9.** Schematic of beam stability measurement diagnostic with metal plate.



**Figure 10.** Sheet beam current distribution diagnostic.

## Results and Discussion

The sheet electron gun using a LaB<sub>6</sub> cathode demonstrated its reliability by delivering 386.5 hours of reliable operation throughout several weeks of experimentation. Furthermore, the cathode survived two venting and pump down cycles without being poisoned and losing its emission characteristics. Electron beam current of 320mA was measured from the 0.03cm<sup>2</sup> emitter area, which corresponds to a current density of 10.7A/cm<sup>2</sup>. The gun required 50 watts of ohmic power to produce this emission level during pulsed operation. A graph of the beam current as a function of the beam voltage and ohmic power is shown in figure 11.

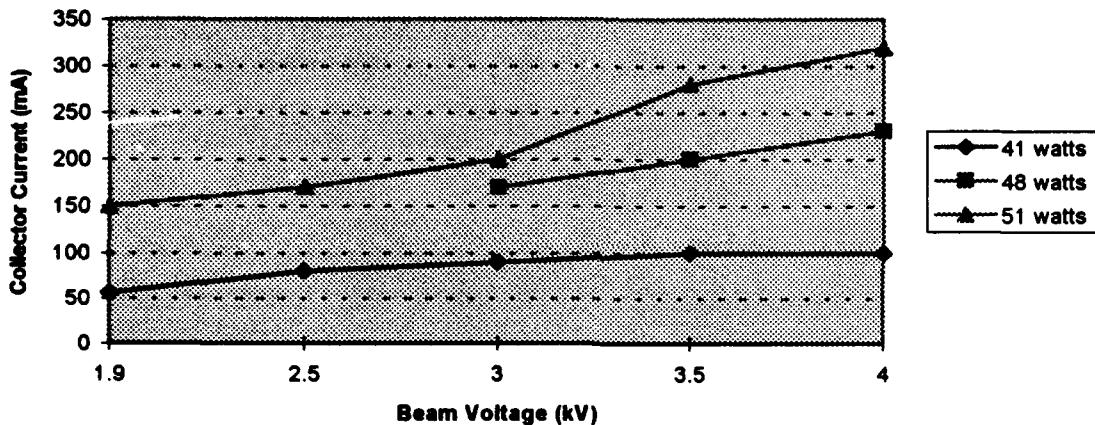


Figure 11. Beam current as a function of beam voltage for different ohmic power level.

This rugged high current sheet electron emitter system enabled a systematic study of beam propagation under various electron device configurations. In the first experiment, the electron beam was allowed to propagate freely without the influence of the metal plate and was only confined by the magnetic field. A thin sheet electron beam confined by a magnetic field does not maintain its initial shape, but eventually breaks up into a series of curved fragments. This occurs because any initial local disturbances in the beam, such as a deflection or density variation, give rise to an imbalance in the space charge field in such a direction as to further increase the disturbance. This indicates a beam instability. Research and experimentation on the techniques to

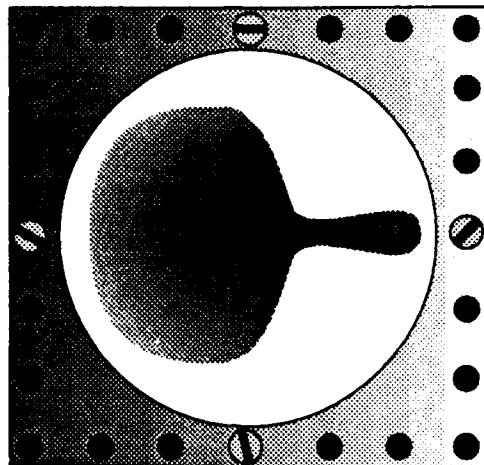
suppress these instabilities are necessary for application of these beams in microwave power tubes.

The first experiment served to visually identify the beam instabilities. The metal plate and the current probe were fully retracted so that the space charge field would not be distorted by their presence. The phosphor screen was placed at distances ranging from 2.5 cm to 4.4 cm away from the emitter. As the phosphor screen moved along the axis of beam propagation, the beam was intercepted by the screen and a cross section was made visible. At each position, the shape of the beam was observed visually and photographed from the window. The electron beam was seen as a blue glow on the phosphor screen. The brightness was proportional to the charge density. Therefore, a stable beam would appear as a clearly defined thin blue line whereas an unstable beam would appear as an unfocused blue area.

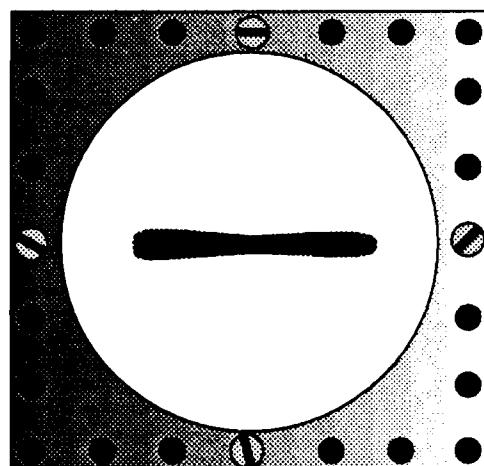
The sheet-like beam did not maintain the same beam thickness along its propagation path. The current density distribution changed significantly from one location to the next. Figures 12 (a) through (c) gives an example of these variations. In figures (a) and (c), half of the beam appears stable while the other half appeared as a diffuse faded glow. The unstable half seemed to fluctuate above and below the plane of the beam. However, it was not clear how much of this phenomenon was time dependent. It is possible that the charges actually did spread out and then converged again. The imbalance in the space charge field appears localized to 2.5 cm and 4.4 cm from the emitter, whereas the beam converged nicely at 3.8 cm from the emitter (see figure 12b). Most of these observations were made at low emission levels (approximately  $0.17\text{A}/\text{cm}^2$ ) because the phosphor screen was easily saturated. The entire screen area glowed blue when the collector saturated thereby obscuring the beam. Changing the high voltage potential difference between the cathode and anode did not improve beam stability. The same phenomenon of beam instability was observed at higher emission levels.

The phosphor coating interfered with making current measurement at the collector. The collector current trace, shown in figure 13, shows two switching transients instead of the expected single pulse. The phosphor screen acted like a capacitor instead of a conductive surface. Current on the order of  $0.5\mu\text{A}$  was measured from the collector indicating that the phosphor was basically non-conductive. The beam current could not penetrate the phosphor coating on the stainless steel collector and the measured current was the result of stray charges. The application

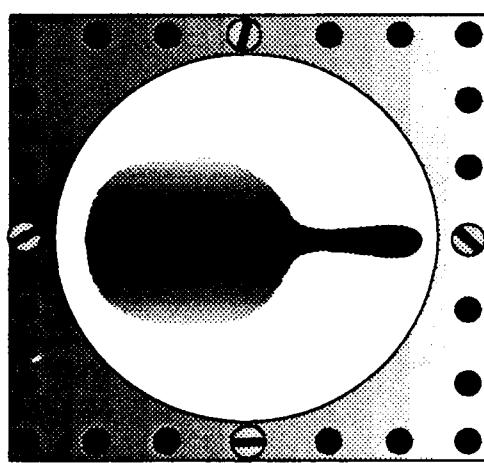
**(a) 25mm from emitter**



**(b) 37.5mm from emitter**

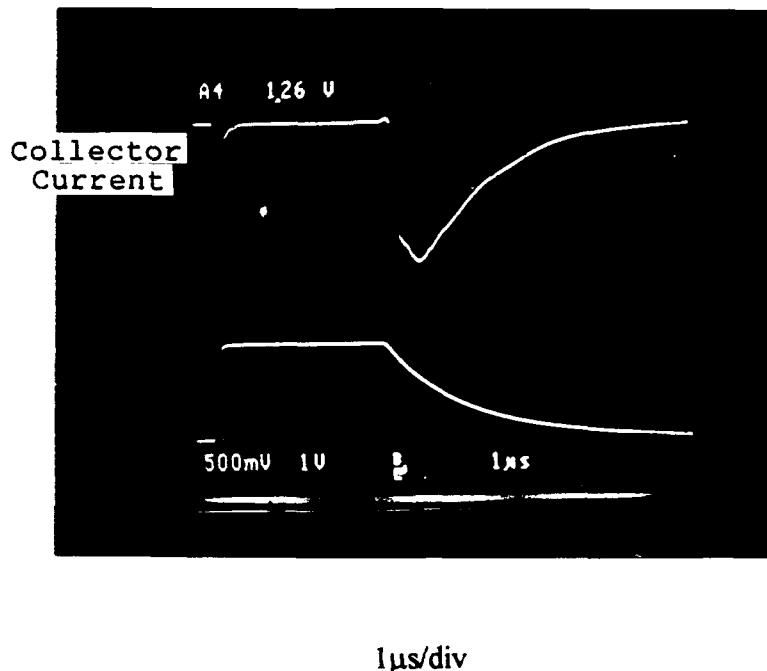


**(c) 44mm from emitter**



**Figure 12. Sheet beam current distribution at 3 locations along the axis of propagation.**

of a bias voltage to the phosphor screen failed to increase its conductivity. As a result, the metal plate was used raised up in front of the phosphor screen to measure beam current by blocking its path.



1  $\mu$ s/div

Figure 13. Collector current measured from the phosphor screen.

During the first 24 hours of operation, there were several dark spots in the beam. Occasionally, the whole phosphor screen would flash blue due to a sudden discharge from the gun. Later, as operation continued, the spots became less prevalent and there were fewer gun discharges. This was a result of the filament conditioning process as contaminants were boiled away. Throughout the experiments, one half of the beam remained brighter than the other half. There are two probable causes for the beam having higher current density on one side: (1) the filament was not evenly heated, (2) the filament was not perfectly level with the plane of the focus electrode or the anode. Unfortunately, the gun was too far recessed from the window and, consequently, the emitter temperature could not be measured. In addition, the filament may have changed position due to thermal expansion. This problem can be eliminated in the future with extra alignment procedures during assembly of the emitter. The filament height can be leveled with respect to the base plate. The focus electrode and anode can be shimmed. The heater leads can be bent to exert pressure on the filament more evenly.

In the second experiment, a metal plate was placed in front of the phosphor screen to evaluate the stabilizing effect of the beam's interaction with the plate surface. The plate was slightly over 1 inch long, and one end terminated at a 45 degree angle. This allowed the phosphor screen to approach the plate very closely and be visible from the viewing port. The metal plate simulated the metal grating in a mm wave source device such as the Orottron.

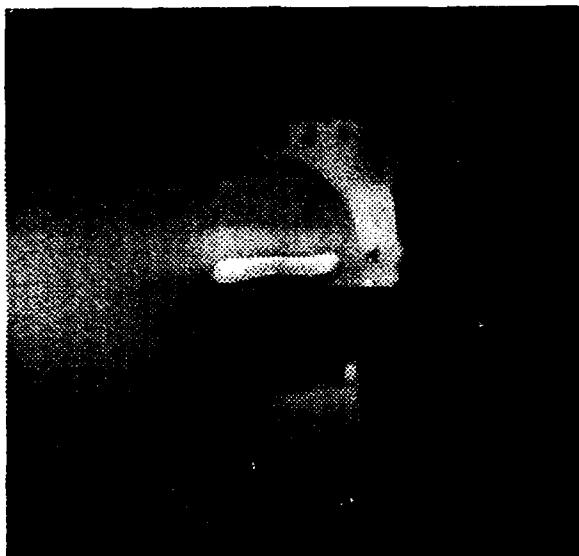
For this experiment, heater power was increased to 47.5 watts thereby increasing beam instability. The metal plate was gradually moved up toward the beam using the tip/tilt height adjustment screws. The plate surface was kept as parallel as possible to the beam through careful visual monitoring of the plate's position. The beam's plane of propagation was verified by blocking the beam completely with the plate, and then lowering the plate while measuring percentage of the beam's current being blocked. Once the location of the beam was established, the plate was moved to just below the beam.

Higher beam voltage caused the beam to move up and away from the plate surface. Also, the increased emission caused the phosphor screen to saturate. Therefore, this experiment was performed at 2 kV beam voltage and 55mA beam current instead of 3kV as used in the last experiment.

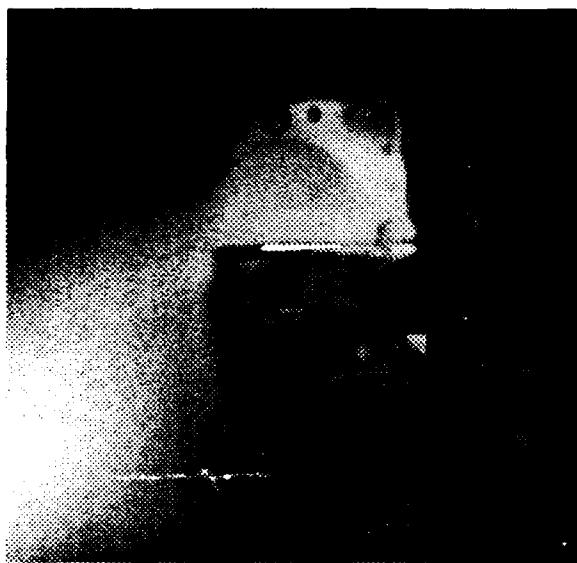
The profile of the beam became thinner, sharper, and more stable as the plate was moved closer to the beam. Figure 14 shows the increase in beam stability with respect to plate distance from the beam.

In the third experiment, the half length metal plate was replaced with a full length (5 cm) plate. The phosphor screen was replaced with a piece of bare copper as the collector. The plate's orientation was adjusted such that it was parallel to the beam. Its height was adjusted such that the beam interacted with the plate's surface but lost less than 20 percent of its total current. Since the beam was not visible on the collector, the beam's position was determined using the current probe. As the plate was brought into contact with the beam, the resulting interaction would change the beam's location. After repeated adjustments, an optimal setting was established. The current probe was then lowered into the sheet-like electron beam to map the current density along the length of the beam.

Typical current waveforms from the experiment are shown in figure 15. The top trace, in the upper photograph is a current probe output which shows the beam current as a function of



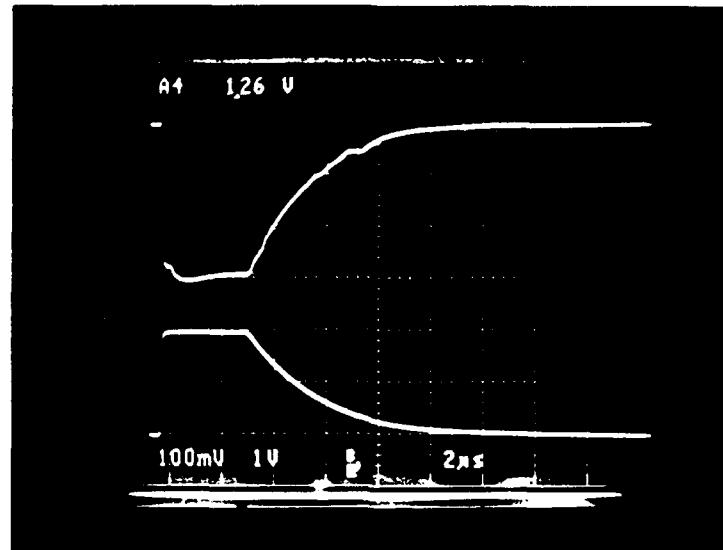
(a)



(b)

**Figure 14.** Sheet-like electron beam profile: (a) with metal plate 1.4mm below the beam, (b) with beam grazing the plate surface.

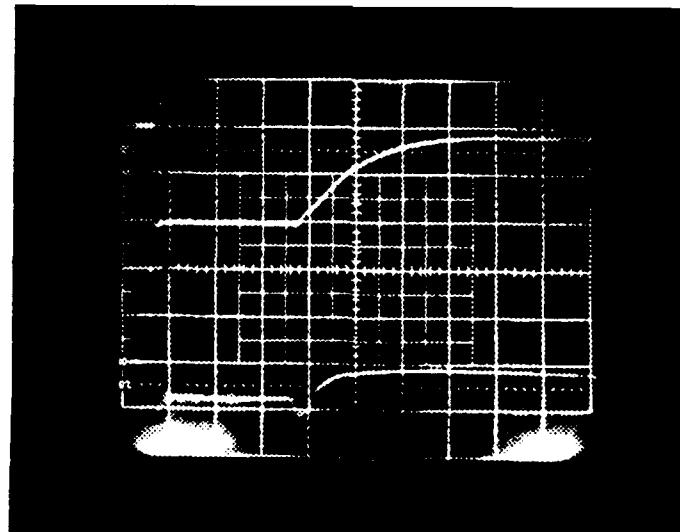
Current probe  
2mA/div



2μs/div

Collector current  
100mA/div

Plate current  
10mA/div



1μs/div

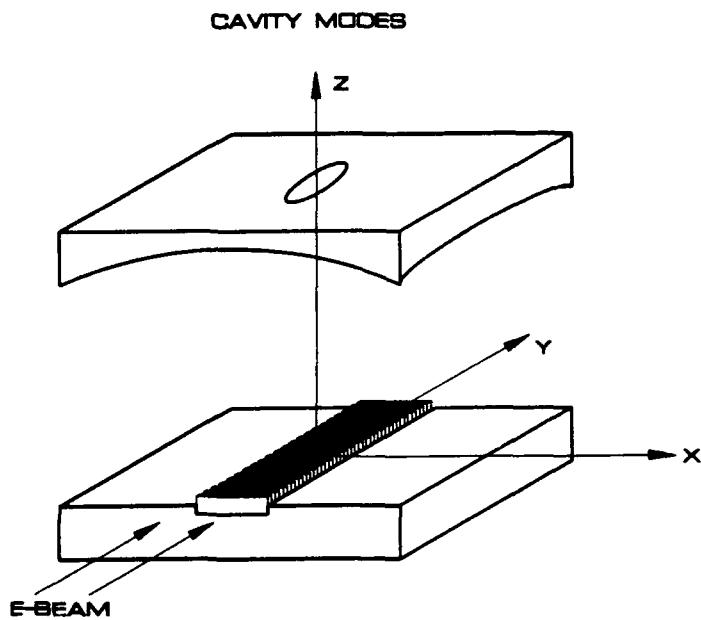
**Figure 15.** Sheet-like electron beam test data: typical current waveform.

time. The lower trace in the same photograph shows the beam voltage, which is held at 2kV for approximately 3  $\mu$ s during the pulse. The top trace in the lower photograph shows the collector current waveform with a peak collected current of 200mA. The lowest trace shows the fraction (<20%) of current that was intercepted by the metal plate.

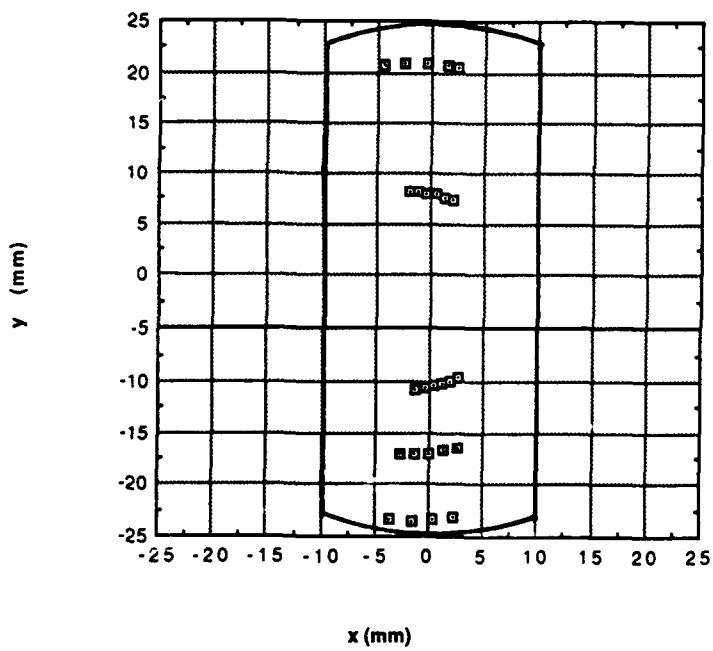
Figure 16 shows the coordinate geometry for measurements. (A whole orotron cavity is shown.) The electron beam moves in the y-direction along the metal plate. Cross-sections of the beam in the z-direction (through the thickness of the sheet) were measured at six y-locations for various x. The actual current probe moved in a rotary direction. Its z position and  $\theta$  position were measured. ( $\theta$  was typically changed in 5° increments, while z was changed in 0.001 inch (25.4 micron) increments. The x and y position, relative to the metal plate below the sheet electron beam, were calculated from  $\theta$  and the known location of the probe used. Only one of the three probes intersected the electron beam at a given time.

Figure 17 shows all the positions where measurements were taken with the current probe. On figure 17, the emitter would be located at -6mm < x < +4mm and y = -35mm. The width of the sheet-like electron beam along the length of propagation can be determined from these cross sections. Data from only five of the cross sections is included because the sixth cross section produced intermittent current readings. At y equal +15mm, the intermittent current readings made the beam appear to be 50 microns thick when the current probe was probably losing connection. The other cross sections produced a beam profile consistent with our predictions.

Beam thickness and current density at a given x-y position were measured by moving the probe in the z-direction increments of 0.001 inch, or 0.025 millimeter. A sample current measurement is shown in Figure 18. The pin could be lowered from above the beam to below the beam into a groove in the lower plate. (The plate was not completely parallel to a given probe z-position, and z = 0 was not accurately calibrated. The variation in z from corner to corner of the plate was about 1.5mm when it was aligned as carefully as possible with the sheet-beam, which followed the magnetic field lines.) The thickness of the beam and intercepted current were measured from the graphed data at each point. The intercepted current maximized when the probe is all the way through the beam. As the probe is raised through the beam (increasing z), the current starts to drop when the probe moves past the edge of the beam. The current dropped



**Figure 16.** Coordinate geometry for measurements.



**Figure 17.** Positions where beam current was measured. X and Y are coordinates on the surface of the plate. The electron beam moves in the y-direction.

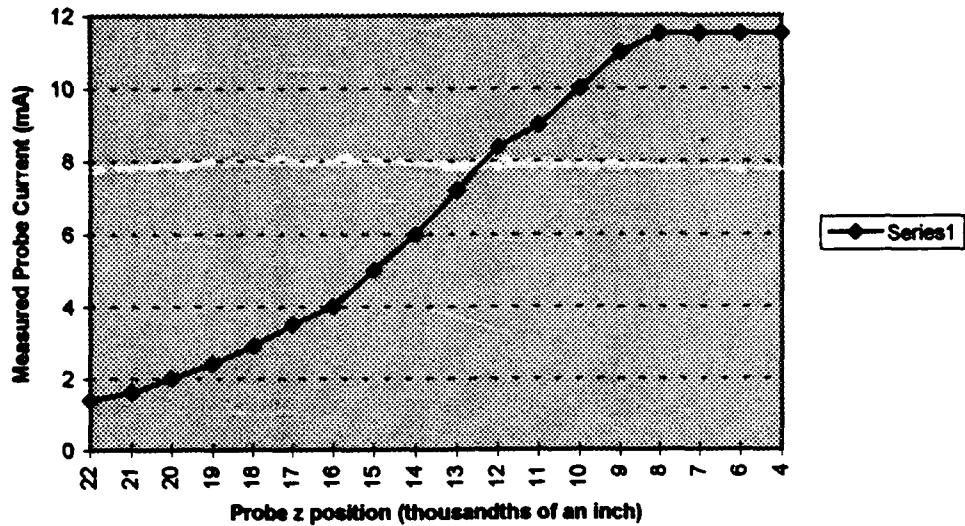


Figure 18. Measured current vs. probe z-position for probe #3 at 140 degrees angle, corresponding to  $x = 0.32\text{mm}$ ,  $y = -23.37\text{ mm}$ .

until it hit a residual background level above the beam, where it fell off slower. This background could be due to current scattering off the plate. The thickness of the beam was taken from where the current fell 0.5mA below the peak value to 0.5mm above the floor. Thus, in figure 18 the thickness would be taken as 10 mil (or 0.25mm) and the intercepted current as 8.5mA.

Figure 19 shows a cross section of the beam in the x-direction taken at a separate time at  $y=-10\text{mm}$ , with the probe all the way through the beam in the z-direction. This shows that the beam is lopsided, with higher current to one side (consistent with our photographs). With everything running properly, we expected the beam width from the 1cm cathode to be about 8mm, although now it was currently 6mm.

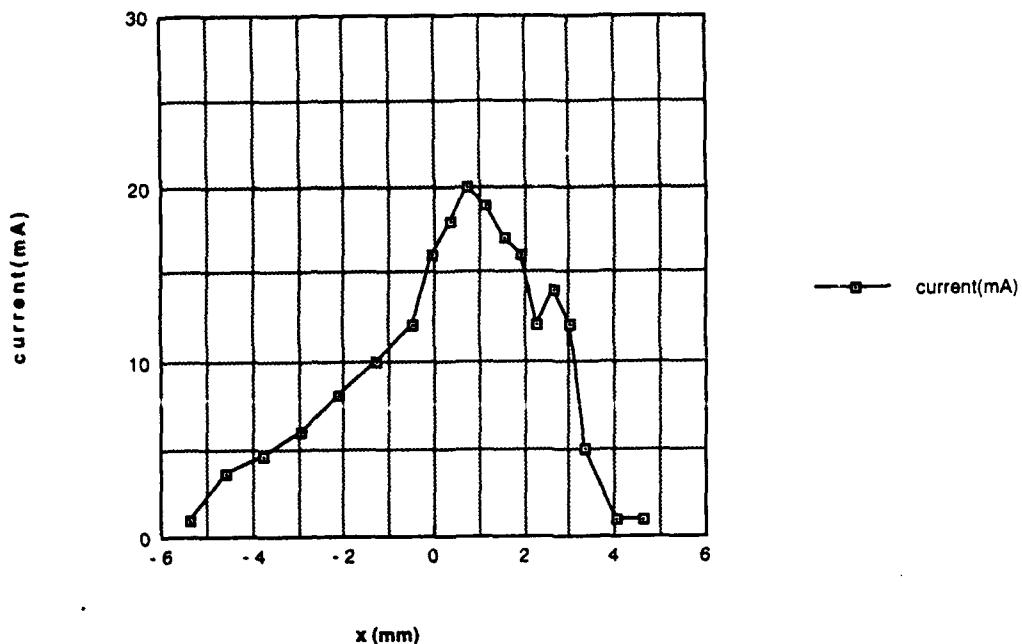
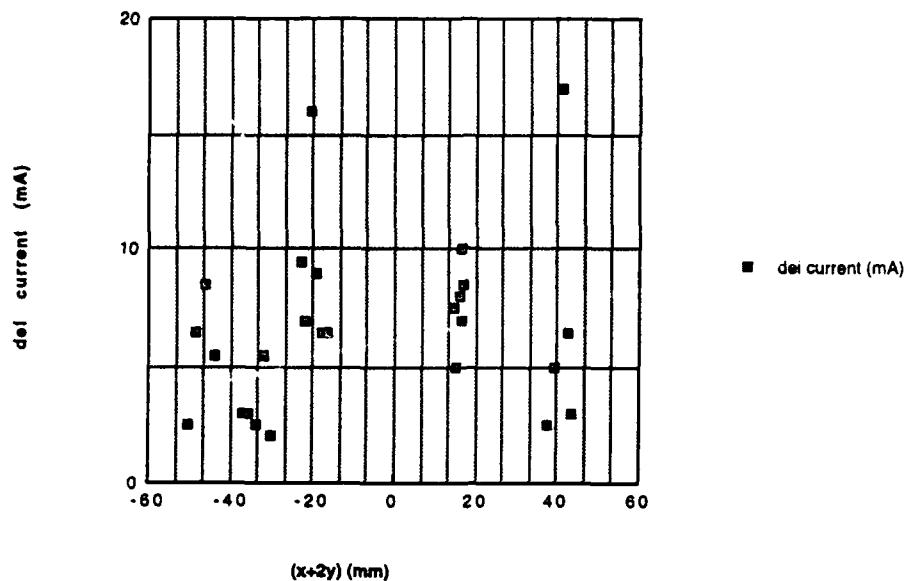


Figure 19. Electron beam current profile across the width of the beam at  $y = -10\text{mm}$ .

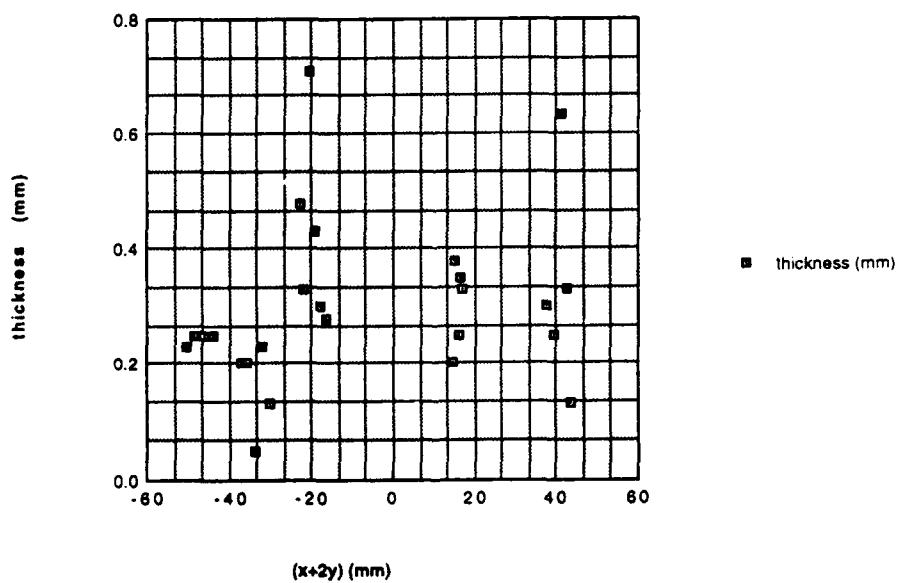
A tabulation of the measured data at different positions is given in table 1. The data points include the  $x$  position,  $y$  position, thickness, and current within the thickness. For graphing purposes, thickness and current are plotted against the quantity  $x+2y$  in figure 20. Note that on average the thickness is consistent with the cathode thickness of  $0.3\text{mm}$ , although the thickness and current increased towards the center at some locations. For microwave devices of interest such as the orotron, it will be important that the current density at the surface of the slow wave structure or grooved metal plate be as high as possible. The test apparatus can now be used during further research to optimize the current density distribution.

Data Point	X (mm)	Y (mm)	Thickness (mm)	Current (mA)
1	-3.555	-23.443	0.230	2.500
2	-1.618	-23.491	0.250	6.500
3	0.316	-23.371	0.250	8.500
4	2.232	-23.082	0.250	5.500
5	2.756	-16.406	0.130	2.000
6	1.420	-16.765	0.230	5.500
7	0.057	-17.007	0.050	2.500
8	-1.320	-17.120	0.200	3.000
9	-2.705	-17.131	0.200	3.000
10	2.665	-9.556	0.280	6.500
11	1.925	-9.934	0.300	6.500
12	1.156	-10.246	0.430	9.000
13	0.362	-10.489	0.710	16.000
14	-0.450	-10.663	0.330	7.000
15	-1.274	-10.765	0.480	9.500
16	-1.938	8.255	0.200	7.500
17	-1.108	8.210	0.380	5.000
18	-0.286	8.094	0.250	8.000
19	0.523	7.906	0.350	10.000
20	1.312	7.649	0.350	7.000
21	2.076	7.324	0.330	8.500
22	2.422	20.504	0.130	3.000
23	1.468	20.678	0.330	6.500
24	-0.456	20.899	0.630	17.000
25	-2.393	20.952	0.250	5.000
26	-4.327	20.836	0.300	2.500

Table 1. Measured thickness and intercepted beam current as a function of x and y position.



(a)



(b)

**Figure 20.** Electron beam current and thickness as a function of position. (a) delta current, (b) thickness.

## **Conclusions**

The proposed novel sheet-like electron emitter system was designed, built, and tested. This project has produced a reliable electron gun that will facilitate the systematic study of the beam's propagation stability. The LaB<sub>6</sub> emitter design successfully demonstrated its reliability by delivering 386.5 hours of operation throughout the weeks of experimentation. In addition, the cathode survived two venting and pump down cycles without being poisoned or losing its emission characteristics. A current density of 10.7A/cm<sup>2</sup> was measured while operating on 50 watts of ohmic heating power. It is expected that a current density at the emitter of about 20A/cm<sup>2</sup> can be achieved by operating at slightly higher heating power and temperature. Alternatively, a design with slightly lower heat loss may enable the necessary temperature to be achieved at the 50 W power level.

The novel test fixture with eight permanent magnets produced an extremely uniform magnetic field with magnetic flux in the same direction as the electron flow. The tip/tilt mechanism and the current probe allowed us to position the metal plate so that close interaction with the electron beam was achieved. Based on the experiences gained from this program, an alignment procedure can be developed to simplify future research.

The expected beam propagation instabilities were corroborated visually. The measured beam current distribution showed some variation in beam thickness and current density along the axis of propagation. The nearby presence of a metal plate leads to significant stabilization of the beam. Further research can lead to optimization of the beam characteristics for particular device applications.

## **Recommendations**

This program has successfully demonstrated the feasibility of the novel sheet-like electron emitter system. The emitter system was specifically designed for high power millimeter and submillimeter wave tubes such as an orotron with short period wiggler. The nearby presence of the metal plate or grating stabilizes the beam, allowing it to maintain a very small thickness. In the future, the sheet-beam apparatus can be used to optimize the electron beam characteristics for an orotron millimeter wave tube. We recommend that the work pursued under this effort be combined with a parallel completed Phase I SBIR for an orotron design. A single Phase II effort should be undertaken to build a prototype broadly tunable, narrow bandwidth orotron.

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